Biogas production by means of an anaerobic-digestion plant in France: LCA of greenhouse-gas emissions and other environmental indicators

Chr. Lamnatou[1*], R. Nicolaï [2], D. Chemisana[1], C. Cristofari[2], D. Cancellieri[2]

[1] Applied Physics Section of the Environmental Science Department, University of Lleida, Jaume II 69, 25001 Lleida, Spain

[2] University of Corsica, UMR CNRS 6134, Research Centre George Peri, Route des Sanguinaires, F-20000, Ajaccio, France

*Corresponding author: lamnatou@macs.udl.cat

ABSTRACT

The present article assesses the environmental profile of a real-scale anaerobic-digestion plant that has been developed in France. The system utilises 13652 t of different types of feedstock related to food industry, agriculture, etc. The study is based on Life Cycle Assessment (LCA) according to Global Warming Potential (GWP), Cumulative Energy Demand (CED), ReCiPe midpoint/endpoint and USEtox. The life-cycle inventory includes real data from various sources of waste as well as the transportation distances. By considering the impact of both anaerobic digestion and transportation for the whole system, the following findings have been found: 6430 t $CO_{2.eq}$ (GWP 100a); 67194 GJ_{prim} (CED); 231100 Pts (ReCiPe endpoint single-score: Human health), 146932 Pts (ReCiPe endpoint single-score: Ecosystems), 171568 Pts (ReCiPe endpoint single-score: Resources). Furthermore, USEtox results, for the whole system and by taking into account both anaerobic digestion and transportation, show that based on: 1) Human toxicity/cancer, anaerobic-digestion phase has around 21 times higher value comparing to transportation, 2) Ecotoxicity, anaerobic-digestion phase presents about 77 times higher value than transportation. Regarding the impact of both phases (anaerobic digestion; transportation) per t of waste or per MWh of electricity, the findings show values of 0.5-0.6 t $CO_{2.eq}$ per t of feedstock (or digestate) or per MWh of electricity produced (not net). A separate subsection with comparisons of the present findings with literature studies about LCA of anaerobic-digestion plants has been included. In general,

a good agreement has been observed. Moreover, comparisons of the impact of the electricity produced by means of the present biogas system with the impact of conventional electricity mixes of several countries are presented and discussed, proving the environmental benefits of the proposed anaerobic-digestion plant.

Keywords: Biogas production, Anaerobic digestion; Waste management; Life Cycle Assessment (LCA); Global Warming Potential (GWP); Cumulative Energy Demand (CED); ReCiPe, USEtox

[1]

1. INTRODUCTION

By taking into account that nowadays there are many environmental concerns (global warming, fossil-fuel depletion, etc.) there is a rising interest in energy production by means of renewable energy sources and environmentally-friendly technologies such as biogas production by means of Anaerobic Digestion (AD). In the frame of AD systems, different types of feedstocks (energy crops, manure, by-products from agro-industry, etc.) can be utilised. In order to evaluate the environmental impacts that are related to the production of biogas by means of AD, Life Cycle Assessment (LCA) has been widely adopted, offering useful information about the environmental profile of these types of systems (Bacenetti et al., 2016). In the following paragraphs, selected studies about LCA of AD plants are presented. The investigations have been categorised by the type of waste.

Cremiato et al. (2018), Tagliaferri et al. (2016), Di Maria and Micale (2015), Evangelisti et al. (2014), Gunamantha and Sarto (2012), Zhao et al. (2009), Cherubini et al. (2009), Chaya and Gheewala (2007) and Özeler et al. (2006) conducted LCA about

[1] **ABBREVIATIONS:** AD: Anaerobic digestion; CED: Cumulative energy demand; CHP: Combined heat and power; CML: CML method; $CO_{2.eq}$: $CO_{2.equivalent}$; CTU_e: Comparative toxic unit for ecosystems; CTU_h: Comparative toxic unit for humans; DALY: Disability-adjusted life years; Eco-indicator: Eco-indicator method; EDIP: EDIP method; GHG: Greenhouse gas; GJ_{prim}: $GJ_{primary}$; GWP: Global warming potential; ILCD: ILCD method; IPCC: Intergovernmental panel on climate change; IPCC 2013: IPCC 2013 method; LCA: Life cycle assessment; MSW: Municipal solid waste; Pts: Points; ReCiPe: ReCiPe method; USEtox: USEtox method; (species.yr): Loss of species over a certain area (during a certain time); TRACI: TRACI method; VENOM: A programme about «valorisation energétique de la biomasse par production de méthane»

AD plants that utilise Municipal Solid Waste (MSW). Various waste-management options (AD, landfilling, composting, incineration, etc.) were evaluated (from an environmental perspective). Impact categories such as Global Warming Potential (GWP), Acidification potential, Ozone layer depletion and Eutrophication potential were examined. Methods such as CML, Eco-indicator 95, EDIP and Cumulative Energy Demand (CED) were adopted. With respect to the locations of the AD plants, the studies mentioned above refer to several countries: UK, China, Italy, Thailand, Turkey and Indonesia.

Ruiz et al. (2018), Jin et al. (2015), Bernstad Saraiva Schott and Andersson (2015), Vandermeersch et al. (2014), Righi et al. (2013), Khoo et al. (2010), presented LCA studies about AD plants that utilise food waste. Different environmental indicators/methods (GWP, EDIP, CML, ILCD, CED, ReCiPe) were examined. In certain cases, the option of AD was compared with other waste-management technologies/scenarios. The references cited above refer to the following countries: Spain, China, Sweden, Belgium, Italy and Singapore.

Moreover, Li et al. (2018a), Ruiz et al. (2018), Ramírez-Arpide et al. (2018), Burg et al. (2018), Budde et al. (2016), Fusi et al. (2016), Hahn et al. (2015), Bacenetti and Fiala (2015), Whiting and Azapagic (2014), Bacenetti et al. (2013), De Vries et al. (2012) and Ishikawa et al. (2006) conducted research about LCA on AD plants that use livestock manure as feedstock. Environmental issues based on multiple environmental indicators/methods such as GWP, CED, ReCiPe, ILCD, TRACI and CML were studied. The following countries were examined: Spain, UK, Switzerland, Japan, Mexico, Germany, Italy, China and Netherlands.

In subsection 3.2.1 of the article (literature review), additional LCA studies about AD plants that utilise various types of feedstocks (grass, energy crops, microalgae, etc.) are presented.

Based on review articles about LCA of AD/biogas production (Hijazi et al., 2016; Bacenetti et al., 2016; Paolini et al., 2018; Li et al., 2018b) as well as based on the references cited above, it can be seen that:

1) Most of the investigations examine environmental issues such as GWP, CED, acidification potential, eutrophication potential and ozone layer depletion.

2) There are few studies which evaluate human toxicity and ecotoxicity.

In light of the issues mentioned above, the present article presents an LCA study about the environmental profile of an AD plant. The plant is real-scale, utilises several types of wastes and it has been developed in Corsica, in France. The LCA includes multiple environmental indicators/methods: the commonly used GWP and CED but also the midpoint/endpoint approaches of ReCiPe and issues about toxicity according to USEtox. Comparisons of the impact of the present biogas system with literature findings about AD plants as well as comparisons with conventional electricity generation systems are also provided. The goals of the present study are following presented:

- Evaluation of the environmental profile of a real-scale AD plant based on multiple methods and environmental indicators (including USEtox human toxicity and ecotoxicity, ReCiPe midpoint and endpoint approaches, etc.).
- Investigation of the animal-waste contribution in each impact category. The participation of each type of animal waste (cattle, sheep and poultry) is discussed.
- Comparisons with literature: Certain environmental indicators are compared with findings from literature.

- Assessment of the impact of the proposed AD system based on different functional units: Whole system; 1 t of feedstock; 1 t of digestate; 1 MWh of electricity produced.

The contribution of the present article to the existing literature and the novelty of the investigation are related to the fact that the present LCA study:

- Is based on multiple methods/environmental indicators, including USEtox human toxicity/ecotoxicity, midpoint/endpoint approaches, etc., whereas most of the literature references present commonly studied issues such as CO_2 emissions and CED. An LCA model based on numerous environmental indicators offers a complete picture about the environmental profile of an AD/biogas plant.
- Refers to a real-scale AD plant in Corsica, in France. In literature, there are few LCA studies about real-scale AD plants in France and there is a lack of LCA investigations about the specific case of AD plants in Corsica. Given the fact that Corsica is an island, waste management and production of electricity based on renewable energy sources play a pivotal role.
- Includes findings based on multiple functional units and, in this way, a complete picture about the environmental performance of the AD system studied is provided.

2. MATERIALS AND METHODS

The LCA study has been conducted according to ISO 14040 (2006), ISO 14044 (2006), by considering: 1) Goal and scope definition, 2) Life-cycle inventory, 3) Life-cycle impact assessment, 4) Interpretation.

2.1. Functional units, boundaries, explanations about the LCA

Regarding the functional units, certain results are presented for the whole system. In subsection 2.2 details about the system are presented. In addition, in certain cases, the results are presented per: 1) t of feedstock, 2) t of digestate, 3) MWh of electricity produced. Multiple functional units have been adopted in order to present the environmental profile of the system from different points of view.

The phases of the life-cycle that have been taken into account are the following: 1) Transportation of the waste from the generation site to the location of the anaerobic digesters, 2) The process of AD. The phases related to the pre-treatment of the waste before AD as well as the phases associated with the treatments of the waste after the process of AD have not been taken into account because the energy necessary for these stages is covered by the energy produced by the system.

2.2. Technical characteristics of the AD plant

The proposed AD system is a real-scale plant that has been developed in Corsica, in France. The AD plant includes production of biogas, cogeneration and utilises different types of waste: waste from agri-food industry, organic waste from agriculture (animal manure, etc.), household food waste and used cooking oil. The process of AD produces biogas and the system generates 600 kW of electricity (gross) which covers the needs of a small city in Corsica. In addition to this, there is production of 570 kW heat (gross). The thermal energy is utilised for drying of alfalfa (during winter months) and wood chips (during warm months). A part of the energy produced by the AD plant is used to cover the needs of the system during operational phase (for instance, waste pre-treatment, hygienisation and heat for the process of AD).

Additional information about the technical characteristics of the system is following presented:

- There are two anaerobic digesters (temperature: mesophilic mode (37^{o}C); operating hours: 8147 hours per year; volume: 2000 m^3 each digester).

- The AD plant produces 11484 MWh of electricity/year (net: 4658 MWh/year) and the electricity is injected into the electricity network of EDF (Electricité de France).

- The thermal energy production is 4312 MWh/year (disposable: 3877 MWh/year).
- There is a biogas production of 1735299 Nm^3/year.

The information about the system mentioned above is based on the study that has been carried out during the sizing of the AD unit. The study mentioned above has been conducted by a design office in collaboration with the «Chambre d'Agriculture de Haute-Corse» and the programme VENOM (valorisation energétique de la biomasse par production de méthane). Information has been taken from the feasibility investigation that has been done in June 2017.

An experimental protocol that allows the treatment of substrates on two-level scale based on batch and pilot reactors has been defined. One of the key points of the AD study is related to the characterisation of the digestion profile of the lignocellulosic substrates. As a first step, the time needed to reach the 75% of the maximum biogas potential of the manure has been identified. The experiments have been conducted until the total depletion of biogas production of the substrate. Conditioning of the substrate, chemical characterisation, analysis of the methanogenic potential and modelling of the system have been done.

After the process of AD, 6-month storage by means of 2 storage tanks (of 2000 m^3) for the liquid part and composting for the solid part have been planned. In terms of the quantities of the waste, on an annual basis, the input (before AD process) includes 13652 t of feedstock and the output (after AD process) is 11512 t of digestate. In Figure 1, a schematic of the real-scale AD plant, developed in France (Corsica), is illustrated. At this point it should be clarified that the data given above are based on the real AD system that is presented in Figure 1.

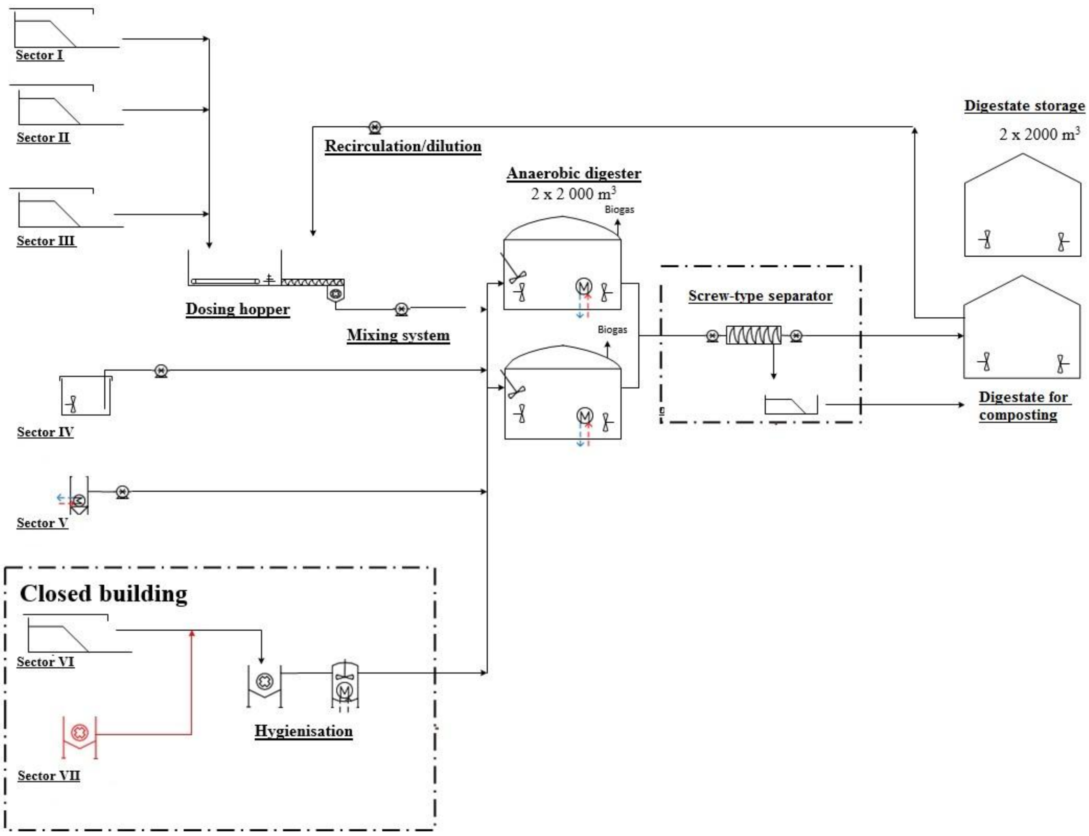


Figure 1. A schematic of the real-scale AD plant which has been developed in France (in Corsica). In Table 1, explanations about Sectors I-VII (feedstocks) are presented.

2.3. Life-cycle inventory and other data

For the calculation of the impact related to AD process and transportation (Table 1), SimaPro 8 software (Source: SimaPro) and ecoinvent 3 database (Source: ecoinvent) have been used. In Table 1, details about the data (masses of each type of waste and transportation distances) are presented.

Regarding the information of Table 1, it should be highlighted that it is based on a real-scale biogas plant that has been developed in Corsica (Figure 1). In the frame of the programme VENOM and based on a collaboration between the «Chambre d'Agriculture de Haute-Corse» and the laboratory «Sciences Pour l'Environnement, Unité Mixte de Recherche 6134 associée au CNRS», different aspects of the plant mentioned above have been evaluated. The aim of the project is to offer practical solutions to waste that is produced in Corsica. The waste quantities as well as the distances of transportation are real data that have been collected from different sectors of Corsica: industry, agriculture, etc. The inputs have been classified by the type of waste (Sector I: waste from animals; Sector II: food industry (fruits, olives, etc.); Sector III: food industry (grape marc); Sector IV: food industry (whey); Sector V: recycling of used cooking oil; Sector VI: food industry (tallow); Sector VII: several types of biowaste). In each case, the calculation of the impact (AD process; transportation) has been conducted by using SimaPro 8 software and ecoinvent 3 database.

Table 1. Sources and types of waste, masses of each type of waste, transportation distances: Data (on an annual basis) based on the real-scale AD plant that has been developed in France, in Corsica.

Source and type of waste	Mass of waste (t)	Transportation distance (km)
SECTOR I Cattle fattening farm: Cattle manure	1500	0
SECTOR I Breeder 1: Sheep manure	84	25
SECTOR I Breeder 2: Sheep manure	86	25
SECTOR I Breeder 3: Sheep manure	88	35
SECTOR I Breeder 4: Sheep manure	90	32.5
SECTOR I Breeder 5: Sheep manure	92	36
SECTOR I Breeder 6: Sheep manure	120	42
SECTOR I Breeder 7: Sheep manure	80	55
SECTOR I Breeder 8: Sheep manure	80	55
SECTOR I Breeder 9: Sheep manure	80	52.5
SECTOR I Breeder 10: Sheep manure	80	55
SECTOR I Breeder 11: Sheep manure	84	17.5
SECTOR I Breeder 12: Sheep manure	120	73.5
SECTOR I Breeder 13: Sheep manure	148	58.5
SECTOR I Breeder 14: Sheep manure	220	130
SECTOR I Poultry company 1: Poultry droppings	120	91
SECTOR I Poultry company 2: Poultry droppings	800	2700
SECTOR I Poultry company 3: Poultry droppings	800	1012.5
SECTOR II Agriculture cooperative 1: Clementine	120	122.5
SECTOR II Agriculture cooperative 2: Clementine	120	175
SECTOR II	120	87.5

Agriculture cooperative 3: Clementine		
SECTOR II Agriculture company 1: Clementine	140	48
SECTOR II Agriculture company 2: Grapefruits	300	805
SECTOR III Company of winemakers 1: Grape marc	1800	1200
SECTOR III Company of winemakers 2: Grape marc	1600	445
SECTOR II Olive mill 1: Olive pomace	275	360
SECTOR II Olive mill 2: Olive pomace	275	536
SECTOR IV Cheese producer 1: Whey	100	247.5
SECTOR IV Cheese producer 2: Whey	1900	4316
SECTOR VI Butchers: Tallow	89	1125
SECTOR VI Delicatessen 1: Tallow	170	1875
SECTOR VI Delicatessen 2: Tallow	170	1875
SECTOR II Hypermarkets and supermarkets: Butchery	156	0
SECTOR II Hypermarkets and supermarkets: Bakery/Pastry	45	0
SECTOR II Hypermarkets and supermarkets: Creamery/Delicatessen	173	0
SECTOR II Hypermarkets and supermarkets: Fruits/Vegetables	77	0
SECTOR VII Hypermarkets and supermarkets: Biowaste	500	0
SECTOR VII Household-waste company: Mainly food waste	500	1876
SECTOR V Company for recycling of used cooking oil: Cooking oil	350	600

2.4. Life-cycle impact assessment methods

The following methods (Sources: SimaPro; ecoinvent) have been adopted:

1) IPCC 2013 GWP 100a V1.00

2) Cumulative Energy Demand V1.08 / Cumulative energy demand

3) ReCiPe Endpoint (H) V1.10 / Europe ReCiPe H/A (single-score)

4) ReCiPe Endpoint (H) V1.10 / Europe ReCiPe H/A (with characterisation)

5) ReCiPe Midpoint (H) V1.10 / Europe Recipe H (with characterisation)

6) USEtox (default) V1.03 / Europe 2004 (with characterisation)

Regarding the methods presented above (1-6), IPCC 2013 GWP 100a refers to the climate change factors of IPCC based on a time horizon of 100 years. CED includes characterisation factors for the energy resources (non-renewable and renewable).

ReCiPe involves midpoint and endpoint approaches, offering useful information for multiple impact categories related to human health, ecosystems and resources. USEtox refers to the characterisation of human and eco-toxicological impacts (PRé, 2014).

3. RESULTS AND DISCUSSION

3.1. RESULTS FOR THE WHOLE SYSTEM

3.1.1. Results for the whole system based on GWP and CED

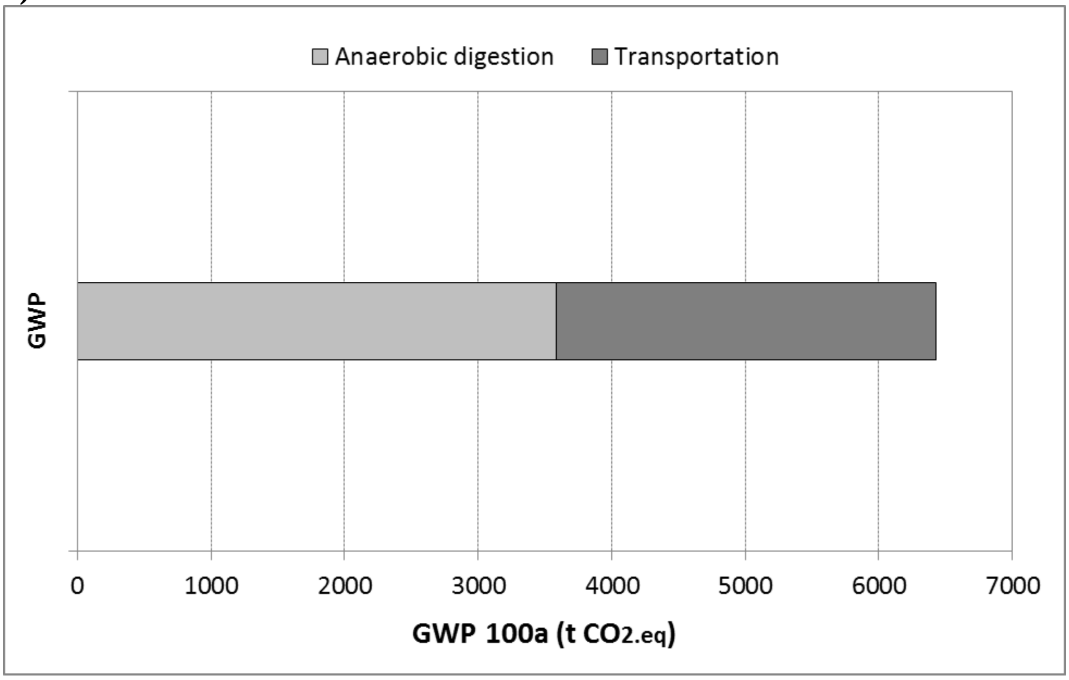
In Figure 2 the findings according to GWP 100a (Figure 2a) and CED (Figure 2b) are illustrated. From Figure 2 it can be noted that:

1) By taking into account both AD and transportation, there is a total impact of 6430 t $CO_{2.eq}$ and 67194 GJ_{prim}.

2) The process of AD presents a GWP that is 741 t $CO_{2.eq}$ higher than the one of transportation whereas transportation shows double CED in comparison to AD.

It should be noted that a great part of the total GWP 100a (41%) and CED (50%) of the AD process is due to animal manures. More analytically, poultry droppings present the highest impact with a total score of 4662 GJ_{prim} and 671 t $CO_{2.eq}$. The animal waste with the second highest impact is sheep manure with the following results: 3935 GJ_{prim} and 566 t $CO_{2.eq}$. Cattle waste shows considerably lower scores: 2161 GJ_{prim} and 238 t $CO_{2.eq}$. In relation to the findings presented above, it should be highlighted that cattle manure is associated with one farm whereas poultry droppings and sheep manure are related to 3 poultry companies and 14 sheep breeders, respectively (Table 1).

a)



b)

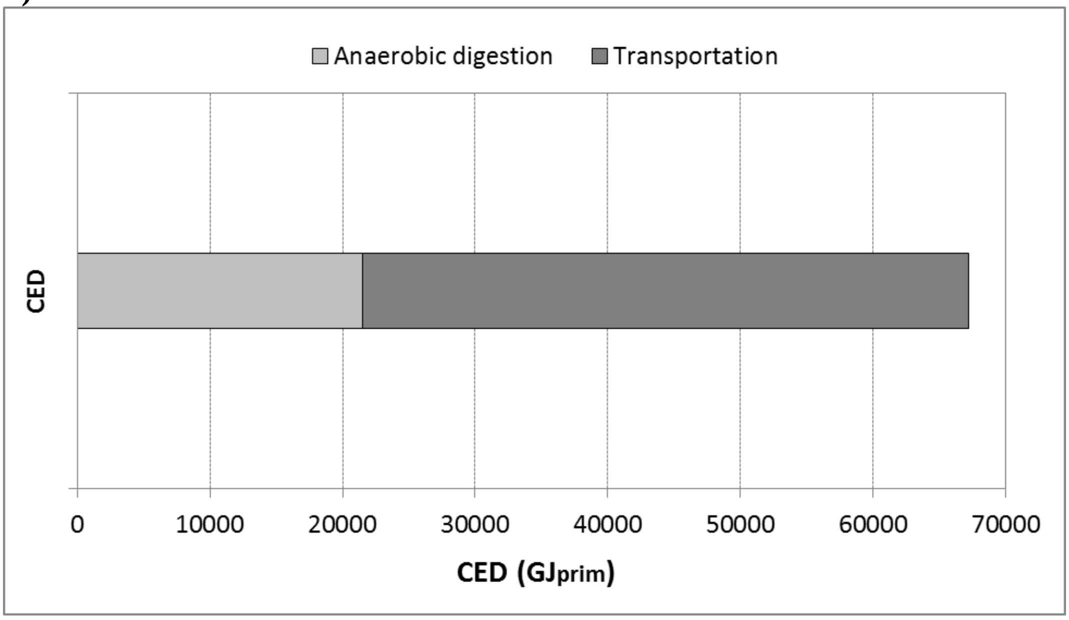


Figure 2. Results for the whole system in terms of anaerobic digestion and transportation, based on: a) GWP 100a (in t $CO_{2.eq}$), b) CED (in GJ_{prim}).

3.1.2. Results for the whole system based on ReCiPe endpoint/single-score

In Figure 3, the findings according to ReCiPe endpoint single-score are presented. From Figure 3 it can be seen that:

1) In terms of the categories of Human health and Ecosystems, the process of AD presents higher scores in comparison to transportation. More analytically, these differences are 8115 Pts and 25399 Pts, for Human health and Ecosystems, respectively.

2) Concerning the category of Resources, the score of transportation is double than the one of AD.

3) By taking into account the impact of both transportation and AD, the total scores are: 231100 Pts for Human health, 146932 Pts for Ecosystems and 171568 Pts for Resources.

With respect to the participation of the animal manures to the total impact of the process of AD, there is a contribution of 44%, 41% and 48% for the categories of Human health, Ecosystems and Resources, respectively. In Table 2, details about animal-waste impact are presented. It can be seen that poultry droppings show the highest score in all the endpoint categories (Human health, Ecosystems, Resources) presenting values which range from 10704 to 23131 Pts, depending on the impact category. Sheep manure is the animal waste with the second highest impact. Cattle manure presents considerably lower scores in comparison to the other two types of animal waste (poultry; sheep). More analytically, the differences between cattle manure and sheep/poultry waste range from 988 to 13299 Pts, depending on the case (Table 2).

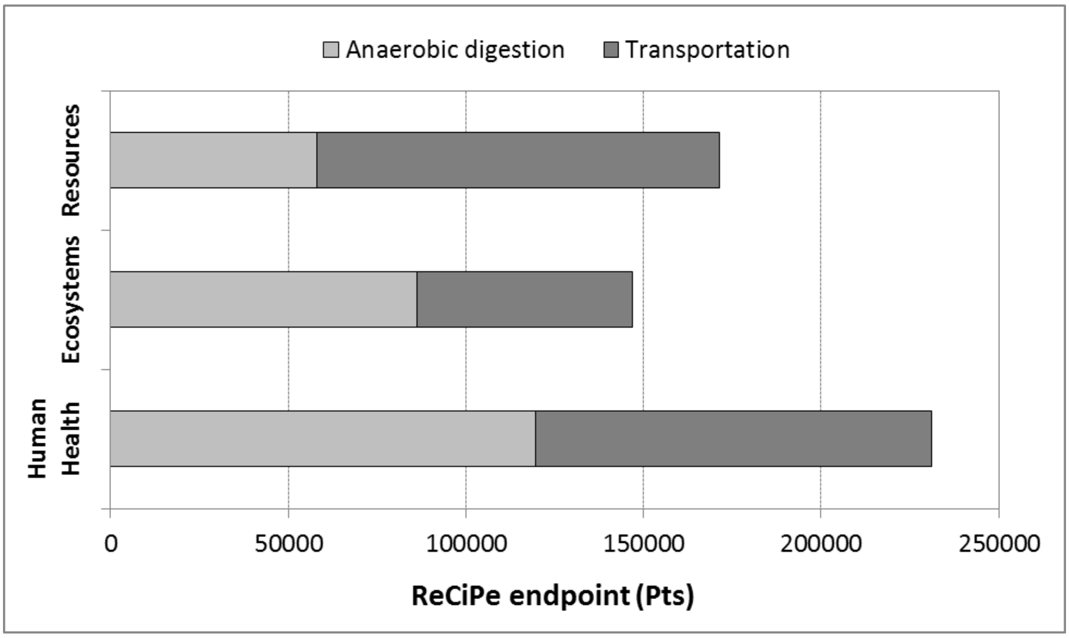


Figure 3. Results for the whole system in terms of anaerobic digestion and transportation, based on ReCiPe endpoint single-score (in Pts).

Table 2. Results for animal waste, based on ReCiPe endpoint single-score (in Pts).

Type of animal waste	Human health (Pts)	Ecosystems (Pts)	Resources (Pts)
Cattle manure	9832	6795	8048
Sheep manure	19527	13078	9036
Poultry droppings	23131	15492	10704

3.1.3. Results for the whole system based on ReCiPe endpoint with characterisation

In Table 3 the findings according to ReCiPe endpoint with characterisation are presented. In Table 3, Disability-Adjusted Life Years (DALY) scores include the following impact categories: Climate change/human health, Ozone depletion, Human toxicity, Photochemical oxidant formation, Particulate matter formation and Ionising radiation. Moreover, in Table 3, (species.yr) values include the impact categories of Climate change/ecosystems, Terrestrial acidification, Freshwater eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Agricultural land occupation, Urban land occupation and Natural land transformation. From Table 3 it can be noted that in both cases (DALY and (species.yr)) the process of AD presents higher impacts in comparison to transportation; however, these differences are not pronounced.

Regarding the contribution of the animal manures to the total AD impact, according to DALY the animal waste shows percentages that vary from 39% to 66% and according to (species.yr) these percentages range from 33% to 53%, depending on the impact category. More analytically, poultry droppings present the highest total DALY value (1.17 DALY). Sheep manure is responsible for the second highest total DALY score (0.99 DALY). On the other hand, cattle manure shows a total DALY impact that is almost half in comparison to the other two types of animal waste (sheep; poultry). With respect to (species.yr), poultry droppings and sheep manure are responsible for the first and second highest score: 0.007 and 0.006 (species.yr), respectively. Furthermore, cattle manure presents almost half total (species.yr) impact in comparison to sheep and poultry waste.

Table 3. Results for the whole system, in terms of AD and transportation, based on ReCiPe endpoint with characterisation.

	DALY	**(species.yr)**
AD	6.04	0.04
Transportation	5.63	0.03

In Figure 4, details about the impact in each ReCiPe endpoint category (with characterisation), are presented. From Figure 4, it can be noted that:

1) In 11 of the 15 impact categories, the phase of AD shows higher values in comparison to transportation. More analytically, these categories are related to damage to human health and ecosystems.

2) For the categories of Ozone depletion, Photochemical oxidant formation, Particulate matter formation and Urban land occupation, transportation presents higher scores comparing to AD.

3) Regarding Climate change/human health, the process of AD presents 0.69 DALY higher impact than transportation. Concerning the category of Particulate matter formation, transportation shows 0.28 DALY higher score in comparison to AD.

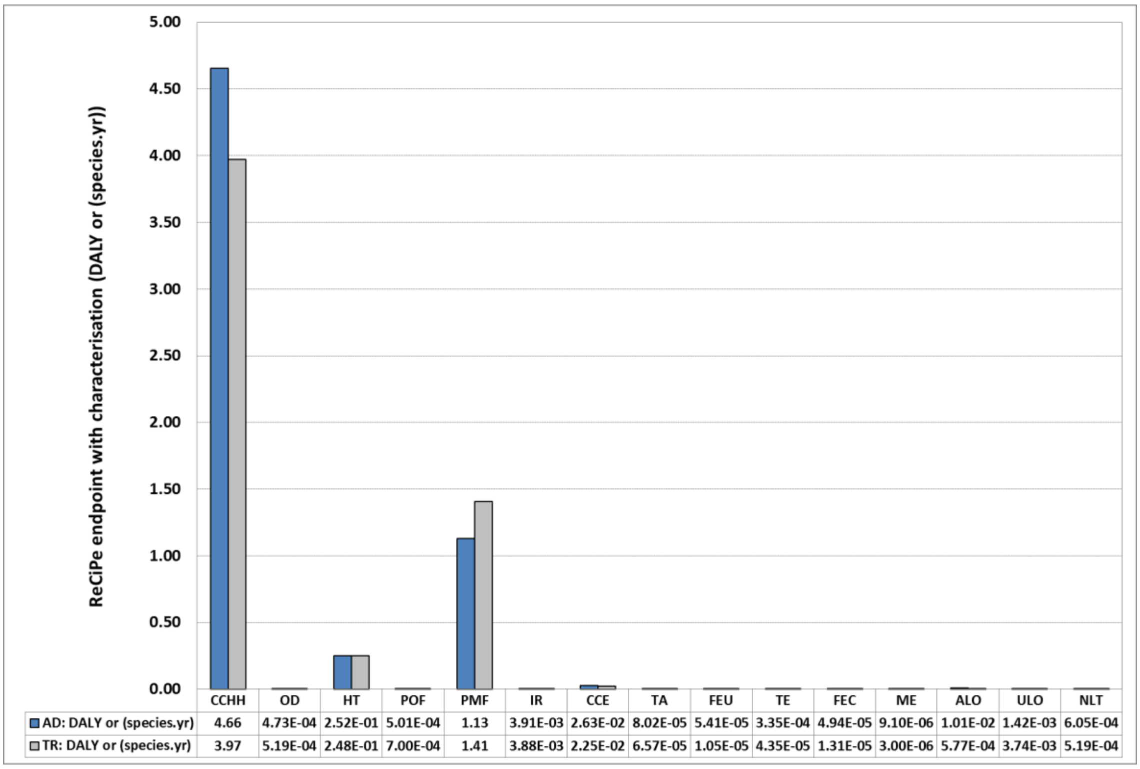


Figure 4. Results for the whole system in terms of anaerobic digestion and transportation, based on ReCiPe endpoint with characterisation. The results are presented in DALY or (species.yr), depending on the impact category (at the beginning of subsection 3.1.3 definitions are provided). Explanations about the symbols that are included in the graph: AD = Anaerobic Digestion; TR = Transportation; CCHH = Climate Change Human Health; OD = Ozone Depletion; HT = Human Toxicity; POF = Photochemical Oxidant Formation; PMF = Particulate Matter Formation; IR = Ionising Radiation; CCE = Climate Change Ecosystems; TA = Terrestrial Acidification; FEU = Freshwater Eutrophication; TE = Terrestrial Ecotoxicity; FEC = Freshwater Ecotoxicity; ME = Marine Ecotoxicity; ALO = Agricultural Land Occupation; ULO = Urban Land Occupation; NLT = Natural Land Transformation.

3.1.4. Results for the whole system based on ReCiPe midpoint with characterisation

In Figure 5, the findings according to ReCiPe midpoint with characterisation are presented. From Figure 5 it can be seen that:

1) In 11 out of the 18 impact categories, the process of AD presents higher impacts in comparison to transportation. More analytically, most of these 11 categories are associated with damage to human health and ecosystems.

2) For the categories of Ozone depletion, Photochemical oxidant formation, Particulate matter formation, Urban land occupation, Natural land transformation, Water depletion and Fossil depletion, the phase of transportation has higher scores than AD.

3) In the case of Climate change, Agricultural land occupation and Metal depletion, AD shows 490228 kg $CO_{2.eq}$, 639018 m^2a and 80940 kg Fe eq higher impact in comparison to transportation. Furthermore, for the categories of Urban land occupation, Water depletion and Fossil depletion, transportation presents 112140 m^2a, 1529106 m^3 and 552827 kg oil eq higher scores than AD.

Concerning the participation of animal waste to the total impact of AD, it should be highlighted that in most of the midpoint impact categories the animal manures show percentages which range from 33% to 66%. In Table 4, information about the animal waste with the highest score in each midpoint category is presented. From Table 4 it can be seen that, cattle manure presents the highest impact in 7 out of the 18 categories. Poultry droppings show the highest values in 11 out of the 18 categories. By taking into account that ReCiPe method has connections between midpoint and endpoint categories (PRé, 2014), it can be noted that most of the midpoint categories cited above in the analysis of cattle-waste impact, at endpoint level are related to damage to ecosystems. Furthermore, most of the midpoint categories which are associated with poultry-waste impact are responsible for damage to human health.

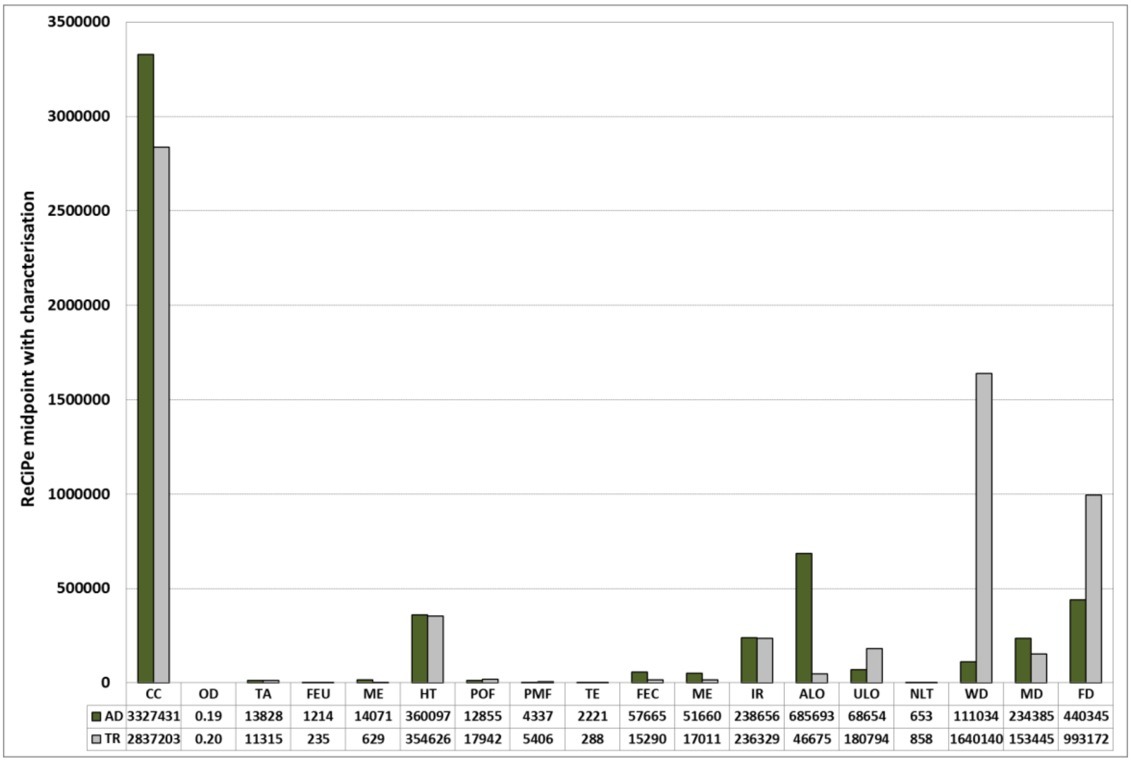


Figure 5. Results for the whole system in terms of anaerobic digestion and transportation, based on ReCiPe midpoint with characterisation. The results are presented in different units, depending on the impact category (in Table 4, details about the units can be found). Explanations about the symbols that are included in the graph: AD = Anaerobic Digestion; TR = Transportation; CC = Climate Change; OD = Ozone Depletion; TA = Terrestrial Acidification; FEU = Freshwater Eutrophication; ME = Marine Eutrophication; HT = Human Toxicity; POF = Photochemical Oxidant Formation; PMF = Particulate Matter Formation; TE = Terrestrial Ecotoxicity; FEC = Freshwater Ecotoxicity; ME = Marine Ecotoxicity; IR = Ionising Radiation; ALO = Agricultural Land Occupation; ULO = Urban Land Occupation; NLT = Natural Land Transformation; WD = Water Depletion; MD = Metal Depletion; FD = Fossil Depletion.

Table 4. The results for animal waste, based on ReCiPe midpoint with characterisation: In each category, the animal waste with the highest score is indicated by X.

ReCiPe midpoint category	Units for each category	Impact of cattle manure	Impact of sheep manure	Impact of poultry droppings
Climate change	kg CO_2 eq			X
Ozone depletion	kg CFC-11 eq			X
Terrestrial acidification	kg SO_2 eq			X
Freshwater eutrophication	kg P eq	X		
Marine eutrophication	kg N eq	X		
Human toxicity	kg 1,4-DB eq			X
Photochemical oxidant formation	kg NMVOC	X		
Particulate matter formation	kg PM10 eq			X

Terrestrial ecotoxicity	kg 1,4-DB eq		X
Freshwater ecotoxicity	kg 1,4-DB eq	X	
Marine ecotoxicity	kg 1,4-DB eq	X	
Ionising radiation	kBq U235 eq		X
Agricultural land occupation	m^2a		X
Urban land occupation	m^2a	X	
Natural land transformation	m^2		X
Water depletion	m^3		X
Metal depletion	kg Fe eq	X	
Fossil depletion	kg oil eq		X

3.1.5. Results for the whole system based on USEtox

In Figure 6, USEtox findings in terms of Human toxicity (Figure 6a) and Ecotoxicity (Figure 6b) are illustrated. From Figure 6 it can be noted that:

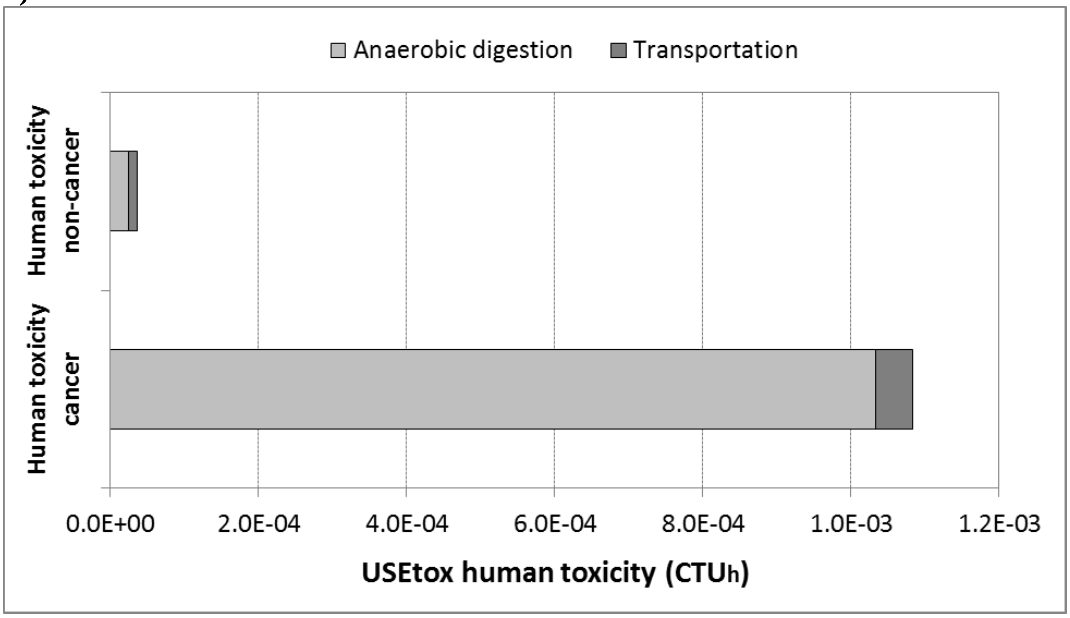
1) In all the cases, the phase of AD shows higher impacts in comparison to transportation and, more analytically, for Human toxicity/cancer and Ecotoxicity the differences between the two phases (AD; transportation) are pronounced.

2) Concerning Human toxicity/cancer, the process of AD presents around 21 times higher score than transportation.

3) With respect to Ecotoxicity, AD shows about 77 times higher impact in comparison to transportation.

Regarding the participation of the animal manures to the total score of AD, according to USEtox, the following percentages have been found: 41% for Human toxicity/cancer, 34% for Human toxicity/non-cancer, 32% for Ecotoxicity. By focusing on animal-waste scores per category it can be seen that: 1) cattle manure shows the highest impact in terms of Human health/cancer, 2) poultry droppings are responsible for the highest impact with respect to Human health/non-cancer and ecotoxicity.

a)



b)

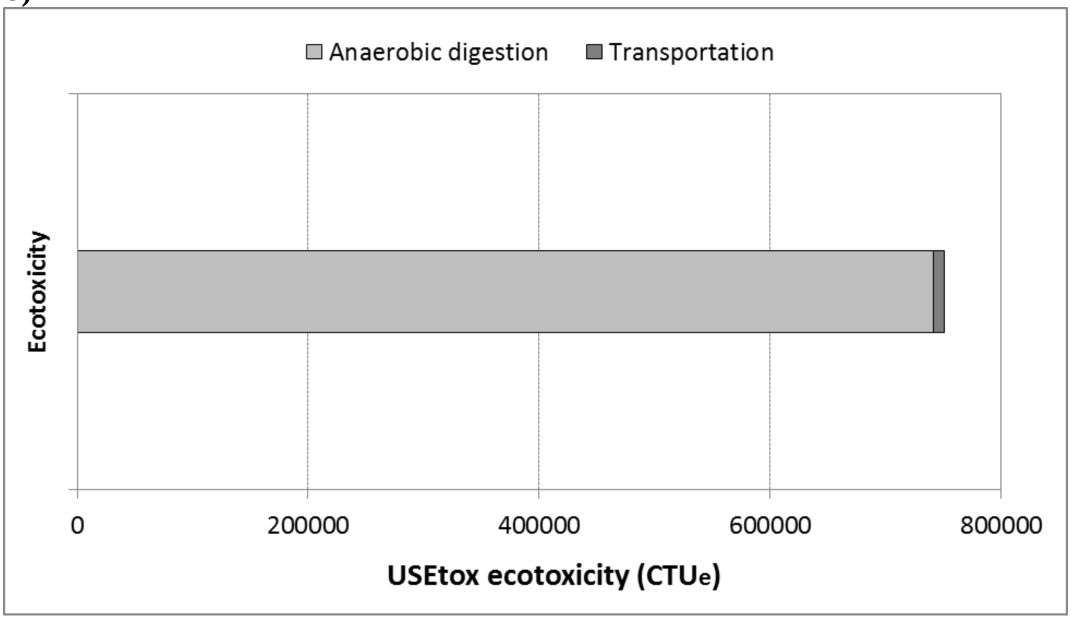


Figure 6. Results for the whole system in terms of anaerobic digestion and transportation, based on USEtox (a: Human toxicity in CTU_h; b: Ecotoxicity in CTU_e).

3.1.6. Discussion about the results presented in subsections 3.1.1-3.1.5

The sources of data (SimaPro; ecoinvent) show that in the case of manure and biowaste treatment by means of AD, the main part of the impact is associated with digester sludge and transportation. Moreover, based on the results of the present study, it can be seen that the impact of each phase (AD; transportation) depends on the method, the adopted approach and the impact category.

As it has been discussed in subsections 3.1.1.-3.1.5, the participation of the animal manures to the total impact of AD shows high percentages. Certainly, this is related to the fact that the animal waste is around 34% of the total mass of the feedstock. In Table 5, an overview about animal-waste impact is presented. It can be noted that poultry droppings show the highest impact in 10 out of the 11 cases studied. Furthermore, cattle waste and sheep manure are responsible for the highest score in terms of USEtox/human toxicity cancer and ReCiPe endpoint with characterisation/DALY, respectively.

Table 5. The impact of the animal waste based on all the cases which have been studied. In each case, the type of animal waste with the highest score is indicated by X.

Method/approach	**Cattle manure**	**Sheep manure**	**Poultry droppings**
GWP 100a			X
CED			X
ReCiPe endpoint single-score: Human health			X
ReCiPe endpoint single-score: Ecosystems			X
ReCiPe endpoint single-score: Resources			X
ReCiPe endpoint with characterisation: DALY			X
ReCiPe endpoint with characterisation: (species.yr)			X
ReCiPe midpoint with characterisation			X (Table 4: poultry droppings show the highest impact in 11 out of the 18 midpoint categories)
USEtox: Human toxicity/cancer	X		
USEtox: Human toxicity/non-cancer			X
USEtox: Ecotoxicity			X

3.2. LITERATURE REVIEW - COMPARISONS OF THE PRESENT FINDINGS WITH LITERATURE – FUTURE PROSPECTS

3.2.1. Literature review

In Table 6, selected references which examine the environmental profile of AD plants are presented. From Table 6 it can be seen that:

1) With respect to the boundaries, there are substantial differences: including (or not) pre-treatment, including (or not) post-treatment, etc.

2) Regarding functional unit, most of the investigations present results in terms of 1 t of waste, 1 MJ (or 1 kWh or 1 MWh) of energy produced as well as in terms of the total production of waste during a certain time period.

3) In some cases, AD is combined with other waste-management options such as landfilling, incineration and composting.

4) Concerning the adopted environmental indicators/methods, it can be noticed that most of the studies are based on GWP, CML, CED and energy inputs whereas there are few investigations which present findings based on ReCiPe, EDIP, ILCD, Ecological footprint, TRACI, Eco-indicator (95 or 99) and about dioxin emissions.

5) The investigations include different types of waste (food waste, MSW, livestock manure, microalgae, etc.).

6) The locations of the AD plants that have been reported in literature vary (Spain, France, China, Italy, Thailand, Australia, Sweden, Indonesia, Netherlands, etc.).

7) The findings of literature verify the environmental benefits of the AD systems that have been studied. For instance, converting animal waste into biogas offers added value to animal manure as a resource of energy and, in addition to this, there is decrease in the environmental impacts. Certain studies focus on the advantages (from an environmental perspective) of the substitution of chemical fertilisers and non-renewable electricity by organic fertilisers and electricity produced by AD/biogas plants.

8) Several studies (Table 6) are based on mesophilic conditions with temperatures 35-40^{o}C (for example, Cremiato et al., 2018). Moreover, some investigations evaluate the combination of thermal treatment with mesophilic conditions (for instance, Hospido et al. (2005): Urban wastewater, Spain).

In relation to point (8), a study about psychrophilic AD of fruit/vegetable waste verified that this waste-management option is feasible, from a technical point of view, and allows the use of low-cost technologies without active heating and other treatments (Martí-Herrero et al., 2019).

Table 6. Selected literature references about LCA of AD plants.

Study and year of the study	Type of waste - Country	Boundaries	Functional units	Method – Environ mental indicators studied	Scenarios	Findings / comments
Hospido et al. (2005)	Sludge generated from the treatment of urban wastewater; Spain	Conditioning (dewatering and/or drying), post-treatment (incineration, pyrolysis or landfill), intermediate stages such as transportation	Management of 1 t of thickened mixed sludge (dry basis)	CML	Scenario 0: AD, mechanical dewatering, land application; Scenarios with incineration and pyrolysis were also examined	AD combined with land application of pasty sludge offers both energy and nutrient recovery
Ishikawa et al. (2006)	Livestock manure; Japan	AD, transportation, waste treatment, etc.	Whole system, etc.	Energy inputs; Energy payback time; CO_2 emissions	Scenarios with different energy inputs were examined	The use of the digested slurry as fertiliser is critical in terms of AD-plant energetic feasibility
Özeler et al. (2006)	MSW; Turkey	From waste to: 1) landfilling or, 2) waste conversion into air emissions and/or emissions to water, 3) waste which regains value	The quantity of MSW that is produced in the districts of Ankara	Non-renewable energy sources; GWP; Acidification potential; Eutrophication potential; Human toxicity potential	Different scenarios were evaluated; One of these scenarios included AD and landfilling	Among all the cases studied, AD presented the lowest contribution to GWP
ADEME (2007)	Separately collected biodegradable waste; France	The boundaries were related to the two basic questions that were examined: Biogas vs. Composting; Field of the investigation: arrival of the separately collected biodegradable waste at the AD plant and use of the biogas and the digestate	Question «Biogas»: Utilisation of 1 Nm³ of crude biogas produced by 8 kg of separately collected biodegradable waste in a methanisation unit; Question: «Composting»: Utilisation of 8 kg of separately collected biodegradable waste (biogas or composting)	Non-renewable primary energy; GWP 100a; Air acidification; Eutrophication	Biogas use vs. composting of the digestate	When the Greenhouse Gas (GHG) emissions of the electricity produced by AD/biogas plants are compared to those of nuclear power plants, it is important to take into account the environmental burdens of nuclear energy (e.g. radioactive waste) and not to focus only on the low CO_2 emissions of the nuclear power plants
Chaya	MSW;	For the AD scheme:	1 t of MSW	Eco-	AD vs. incineration	LCA is a useful tool

and Gheewala (2007)	Thailand	separation, slurry preparation, AD, biogas production, fertiliser production, electricity production, disposal of solid residues (landfill)	managed	indicator 95		in order to find sustainable waste-management scenarios
Cherubini et al. (2009)	MSW; Italy	Scenario 2: Collection of MSW; MSW sorting → Organic part: AD, biogas, composting; inorganic part: combustion, electricity, landfill; ferrous metals: recycling; heavy waste: landfill	The waste produced in one year (city of Roma, 2003): 1460 kt of wastes contained in the ‘‘black sacks’’	Gross energy requirement; Ecological footprint; GWP; Acidification potential; Eutrophication potential; Dioxin emission	Scenario 2: AD, composting, landfill, etc.; Additional scenarios were also examined	Landfilling is not the best option (from an environmental point of view); Energy recycling can offer multiple environmental benefits
Zhao et al. (2009)	MSW; China	Foreground system: directly associated with waste treatment (collection, transportation, MSW to energy, composting, AD, material-recycling facility, landfill); Background system: Production of energy and materials	Disposal of the MSW collected by the central districts of Tianjin city (2006); Total amount of waste: 909160 t	GHG emissions	Scenario 6: Metals, glass, paper, plastics are recycled (30% rate), 50% of kitchen waste is separated and collected in order to be treated by means of AD; Scenarios with incineration, recycling, etc. were also evaluated	Kitchen-waste biological treatment shows potential for further reduction in GHG emissions
Khoo et al. (2010)	Food waste; Singapore	Outputs: electrical energy and bio-compost (bio-compost use has been taken into account); Electricity requirements: Singapore national grid	Food waste produced in Singapore: 570000 t/year	EDIP 2007	One of the scenarios studied: AD, composting, incineration; Additional waste-management scenarios were also examined	The total normalised findings revealed that the small-scale aerobic composting system that was studied is more environmentally friendly than the incinerators; however, it is less ideal in comparison to AD
Foley et al. (2010)	Wastewater; Australia	The raw sewage that arrives at the wastewater-treatment plant; all the discharges; system boundaries included first- and second-order processes	Treatment of 10 ML d^{-1} of raw domestic wastewater during 20 years	GHG emissions; Resources consumed and emissions produced	Several wastewater-treatment scenarios were examined; in certain cases, AD has been included	The study placed emphasis on life-cycle inventory; There is an increase in infrastructure resource consumption when there is lower effluent nitrogen and phosphorus targets for wastewater treatment
Collet et al. (2011)	Microalgae; France	Production, harvesting, concentration of algae; transformation of algae	1 MJ produced by means of combustion	CML	Different scenarios (e.g. in terms of the fertiliser inputs)	The bioenergy-generating process proposed is

		into methane; combustion; construction and dismantling of the facilities; extraction; shipping	in an internal combustion engine		were evaluated	competitive in comparison with others methods of biofuel production
De Vries et al. (2012)	Pig manure; Netherlands	The boundaries vary, depending on the scenarios; One of these scenarios includes: pig production, manure storage, AD, etc.	1 t of substrate (fresh matter) added to the digester	ReCiPe	Different scenarios were studied: Mono-digestion of manure vs. co-digestion with maize silage	Co-digestion with wastes such as roadside grass presented the best environmental profile
Gunamantha and Sarto (2012)	MSW; Indonesia	Collection and transportation of the waste, incineration, gasification, AD, landfilling	1 t of MSW treated (region: Kartamantul)	GWP, Acidification, Eutrophication, Photochemical oxidant formation	Different waste-management options were examined: AD with incineration, landfilling with energy recovery, etc.	In the frame of the evaluation of different solid waste-management scenarios, LCA is a useful tool
Bacenetti et al. (2013)	Pig slurry vs. maize silage; Italy	Cradle-to-grave: all the inputs of the life-cycle from raw material acquisition (or generation by means of natural resources) were considered; all the processes/inputs throughout the life-cycle were included	1 t of fresh matter; 1 kWh of electricity produced by means of a Combined Heat and Power (CHP) system	CED; IPCC (2006)	Full valorisation of net thermal energy; Alternative scenario: the electricity that is generated by means of biogas substitutes the electricity generated by using mainly carbon; Other scenarios were also examined	In comparison to a fossil system that was used as a reference, the electricity production by means of biogas presented GHG savings ranging from 0.188 to 1.193 kg $CO_{2.eq}$/kWh
Righi et al. (2013)	Sewage sludge and food waste; Italy	AD/landfilling scenario: transportation of the organic fraction of the MSW to the digester, operation of the digester and the CHP system, draining of the liquid fraction (wastewater treatment plant), transportation and disposal of the digested matter (landfill)	Management of 3000 t of biodegradable waste fractions; mixing ratio: 1000 t of organic-fraction MSW and 2000 t of sewage sludge	CML	AD/landfilling scenario: Combination of AD with landfill; Additional scenarios with landfill, composting, etc., were examined, including a scenario which combines AD with composting	Anaerobic co-digestion of dewatered sewage sludge and organic fraction of MSW in small-scale plants in combination with composting (as post-treatment) is an environmentally friendly waste-management solution in the case of small communities
Vandermeersch et al. (2014)	Food waste; Belgium	Scenario 1: Generation of food waste (supermarkets), sorting of food waste, AD, electricity, heat, digestate, packaging	Valorisation of 1000 t of food waste	ReCiPe	Scenario 1: food waste, AD; Scenario 2: a bread fraction was used to produce animal feed and a non-bread fraction was used for AD	The high dry matter of the bread-waste considerably influenced the results of the study
Whiting and Azapagic (2014)	Agricultural wastes; UK	Collection of farm waste; AD: production of biogas; cogeneration of electricity and heat: CHP; Storage and use of the digestate	Cogeneration of 1 MWh of heat and electricity	CML 2011	All the waste for AD is generated onsite; Collection by trucks; Hopper and mixer; A total quantity of about 14	The results are influenced by factors such as the kind of feedstock, digestate storage and its application

		(fertiliser)			t of waste/day of waste is fed into the AD system	on land
Evangelisti et al. (2014)	MSW; UK	Foreground system: AD, CHP, treatment and spreading of the digestate; Background system: production of electricity, heat and organic fertiliser, etc.	London Borough of Greenwich: The total amount of organic fraction MSW produced in the borough (35574 t/year)	CML; EDIP97	AD with CHP; Scenarios with incineration, landfilling, etc. were also evaluated	AD is the best option with respect to the total CO_2 and SO_2 savings, when energy as well as organic fertilisers substitute non-renewable electricity production, heat and inorganic fertilisers
Bernstad Saraiva Schott and Andersson (2015)	Food waste; Sweden	Avoided-production option: Production, transportation, food preparation, packaging, incineration or AD (depending on the scenario), etc.	Managing 1 t of food waste from households	GWP	AD vs. incineration	AD environmental profile depends on factors such as the impact of: 1) the fossil fuels, 2) the chemical fertilisers that are replaced by organic ones
Di Maria and Micale (2015)	MSW; Italy	Bins, waste-collection vehicles, incineration and landfilling (or AD, composting, wastewater treatment and landfilling, depending on the scenario)	1 t of organic waste generated in the area studied	CML 2001	AD vs. incineration	Based on the cases studied it was found that if incineration is not viable from an economic point of view, the option AD/composting is recommended
Jin et al. (2015)	Food waste; China	Recycling system using food waste, electricity (input), renewable energy and products (outputs); Process input/terminal, primary treatment, output terminal, recycling system; Subsystems: pretreatment, AD, biogas utilisation, disposal of the digestate, biological deodorisation	1 t of food waste treated in the system	CML-IA	Plant capacity: 250 t/d; Pilot project; A process which combines wet AD with wet heat treatment (thermophilic)	A sensitivity analysis revealed that an increase of 40% in terms of the feed fat content offers 38% higher net energy output
Bacenetti and Fiala (2015)	Animal manure and energy crops; Italy	Energy-crop production, feedstock transportation to the biogas plant, AD, biogas use, digestate storage, management	1 kWh of electricity fed into the electric grid	IPCC (2006): GWP 100a	Scenarios which include the impact of heat valorisation have also been studied	Electricity production by means of AD plants presented a carbon footprint reduction ranging from -0.208 to -1.07 kg $CO_{2.eq}$/kWh, mainly due to the substitution of fossil-fuel energy production
Hahn et al. (2015)	Maize silage, rye silage, grass, liquid manure;	Biomass cultivation and supply, biogas production and storage, biogas converted into biomethane and biomethane grid	1 MJ biogas supplied to the power generator for flexible power generation	Primary energy; GHG emissions; Acidification;	Different scenarios were examined: biogas storage, grid injection, etc.	Systems with flexible biogas production due to the fact that they show reduced biogas

	Germany	injection (including transportation)		Eutrophication		storage requirements, offer higher savings in comparison to systems with continuous biogas production
Budde et al. (2016)	Cattle waste; Germany	Feedstock provision, production, transportation, storage, processing, storage of the cattle manure (solid; liquid), biogas production, CHP, etc.	1 kWh electricity	Energy payback time; GHG emissions; GHG payback time	AD: Replacement of maize silage by liquid and/or solid cattle waste	Thermobarical hydrolysis is feasible for feedstocks such as solid cattle waste and mixture of solid and liquid cattle waste
Fusi et al. (2016)	Maize silage, animal slurry and tomato waste; Italy	Maize cultivation and ensilage, AD, treatment, storage, CHP	Generation of 1 MWh of electricity (fed into the grid)	CML 2001	Five plants were examined: utilising maize silage, slurry and tomato waste and including cogeneration of electricity and heat	The electricity produced by means of biogas was found to be more environmentally friendly than the electricity from the conventional grid that was selected for the comparison
Tagliaferri et al. (2016)	MSW; UK	The analysis included the stages from MSW to CH_4 production (appropriate for grid injection)	1 kg of MSW; 1 MJ of methane produced	GWP, Acidification potential; Ozone layer depletion, etc.	Five scenarios were examined: AD in combination with landfill, incineration, etc.	The functional unit is a key factor which influences the results
Ruiz et al. (2018)	Agri-food waste, sewage sludge, pig/cow manure (base scenario); Spain	Power generation has been assumed as the only function of the system, expanding the boundaries to include biowaste end-of-life management; The following phases have been considered: biowaste transportation, operation and maintenance, biogas plant, avoided impacts	1 kWh injected into the grid	CED; ILCD	Except of the base case, an additional scenario that includes the use of the digestate as fertiliser has been evaluated	The AD of the biowaste that was studied presented negative values in terms of climate change
Cremiato et al. (2018)	MSW; Italy	Base-case scenario: Household waste, collection, separation; Mechanical/biological treatment, composting, incineration, landfilling, etc.	1 t of household waste	CED; CML	Different scenarios in terms of waste-management options were evaluated (AD, incineration, etc.)	The scenarios that included AD and digestate composting presented better performance in comparison to those that included only composting
Boscaro et al. (2018)	Riverbank grass; Italy	Mowing, harvesting, transportation, storage, AD, etc. (depending on the scenario)	1 t of waste	CED; GHG emissions	Different scenarios in terms of storage, transportation, etc. were examined	The incorporation of grass from non-cultivated areas into the AD chain (so as to reduce the needs in terms of

						agricultural feedstock) presented multiple advantages
D'Impo rzano et al. (2018)	*Arundo donax* L. vs. other types of waste; Italy	Inputs/outputs in terms of materials and energy needed for biogas production and CHP	1 kWh of electrical energy produced by means of AD	ReCiPe	One of the scenarios included AD based on 49% of animal slurries, 32% energy crop (maize silage), 19% bio-products; Another scenario: adoption of *Arundo donax* L. instead of silage maize	*A. donax* (due to its high biomass productivity) offered a considerable reduction in the energy-crop impacts
Li et al. (2018a)	On-farm organic residues (dairy manure, corn stover, tomato residue); China	Transportation, pre-treatment, AD, composting, etc.	Treatment of 1 t of dairy manure produced in the farm	TRACI	System 1: Liquid AD (dairy manure); System 2: Solid state-AD (dairy manure and corn stover); Other systems were also investigated	The scenarios that were examined in terms of transportation distances revealed that by locating the AD plant and the composting facility on farm offers environmental benefits
Ramíre z-Arpide et al. (2018)	Nopal cladodes, dairy cow manure; Mexico	Basic scenario: Conventional farming system, Nopal-cladodes and dairy-cow-manure transportation, pre-processing, AD, open digestate storage	1 MJ of bioenergy produced	CML baseline 2001; CED	Basic scenario: conventional farming system and open digestate storage; Alternative scenarios with organic farming were examined	Organic-farming option presented a reduction of 22.5% in GWP
Burg et al. (2018)	Manure; Switzerlan d	Manure management and transportation to the AD plant, emissions from the plant itself, digestate storage	Impact per year for manure management	IPCC (2006): GHG emissions	Different scenarios (for example, in terms of the amount of manure that was treated by means of AD) were examined	AD of manure offers multiple environmental benefits and, for this reason, it should be promoted

3.2.2. Comparisons of the present findings with literature - Discussion

In Table 7, the findings of the present system are compared with literature. From Table 7 it can be seen that:

1) In certain cases, there is quite good agreement between the findings of the present study and those of literature; however, it should be highlighted that a direct comparison is not possible due to differences in terms of the databases, the assumptions, the boundaries, etc.

2) The system of the present study shows an impact of around 0.5-0.6 t $CO_{2.eq}$ per t of feedstock (or digestate) or per MWh of electricity produced (not net).

3) AD plants offer environmentally-friendly electricity production.

In relation to point (3) a discussion is following presented: The proposed AD system shows an impact of 5.85 GJ_{prim}/MWh of electricity produced (not net) whereas several conventional electricity mixes present impacts more than 10 GJ_{prim}/MWh. Based on the report treeze (2014), some examples are following given: In terms of the level "electricity mix, at plant", among the cases that were examined, the Greek electricity mix presented the highest CED per MWh of electricity produced (14.85 GJ-oil-eq/MWh), followed by the electricity mix of India (13.61 GJ-oil-eq/MWh). Moreover, the Polish electricity showed 12.75 GJ-oil-eq/MWh and the Hungarian electricity presented 12.53 GJ-oil-eq/MWh. Certainly the high CED of the electricity mix of a country is associated with high penetration of lignite, hard coal or nuclear energy during electricity production. Furthermore, it should be noted that the French electricity showed the highest nuclear CED (10.21 GJ-oil-eq/MWh). In the report treeze (2014), it was mentioned that the CED-nuclear of the electricity mix of a country is high in countries with high percentages of nuclear energy in their electricity production. In Table 6 (Reference: ADEME, 2007; last column of Table 6), an additional discussion about the environmental profile of nuclear power plants is provided. On the other hand, among the cases that were studied (report treeze, 2014), the Icelandic electricity showed the lowest CED (3.89 GJ-oil-eq/MWh) followed by the Norwegian electricity (4.00 GJ-oil-eq/MWh), Brazilian electricity (5.06 GJ-oil-eq/MWh), electricity utilised by the Swiss railways (6.39 GJ-oil-eq/MWh) and Tanzanian electricity (6.65 GJ-oil-eq/MWh). In the report treeze (2014), it was noted that the electricity-generation CED presents low values in countries with high penetration of hydro power in their electricity production. Moreover, the Icelandic electricity showed the highest renewable CED (3.81 GJ-oil-eq/MWh) (Report treeze, 2014).

With respect to carbon-footprint savings by means of AD, an analytical discussion has been presented by Bacenetti and Fiala (2015). The LCA study mentioned above focused on the carbon footprint of the electricity generation from biogas based on five AD plants in Italy. Different plant sizes (ranging from 100 to 998 kW) and feeding rates (maize and pig slurry, only maize, etc.) were examined. The carbon-footprint savings for the electricity produced by means of the AD plants varied from -0.208 to -1.07 kg $CO_{2.eq}$/kWh. Bacenetti and Fiala (2015) highlighted that these savings are mainly associated with the substitution of the energy produced by fossil fuels. It was also noted that the electricity generated from biogas shows a high potential in terms of GHG mitigation. Moreover, it was mentioned that by means of the valorisation of the surplus heat as well as by reducing transportation distances, lower GHG emissions of the proposed bioenergy system can be achieved. Bacenetti and Fiala (2015) mentioned that the favourable carbon-footprint of biogas production is mainly associated with the credits obtained from replacing the electricity generated by fossil fuels. The biogas process does not sequestrate GHG but it generates electricity that replaces the current electricity mix that has high GHG emissions (Bacenetti and Fiala, 2015). Furthermore, in the report treeze (2014), among the cases that were examined, high GHG emissions (almost double in comparison to the present AD system in Corsica, in France) were found for the following countries: China (1.111 t $CO_{2.eq}$/MWh), Estonia (1.058 t $CO_{2.eq}$/MWh), Poland (1.053 t $CO_{2.eq}$/MWh), Australia (1.032 t $CO_{2.eq}$/MWh). It was noted that GHG emissions show high values in the case of countries with high percentages of hard coal and lignite in their electricity mixes (Report treeze, 2014).

Table 7. Results of the present study and comparisons with literature.

Present study	**Literature: AD plants vs. electricity mixes of several countries**
GWP 100a: 0.47 t $CO_{2.eq}$/t of feedstock (taking into account both AD and transportation)	Tagliaferri et al. (2016), MSW, **AD:** In certain cases, values of 0.5-0.6 t $CO_{2.eq}$/t of waste were found
GWP 100a: 0.56 t $CO_{2.eq}$/t of digestate (taking into account both AD and transportation)	Tagliaferri et al. (2016), MSW, **AD:** In certain cases, values of 0.5-0.6 t $CO_{2.eq}$/t of waste were found
GWP 100a: 0.56 t $CO_{2.eq}$/MWh of electricity produced (not net)	Bacenetti et al. (2016), review paper, different types of waste, **AD:** Several references presented values around 0.4-0.5 t $CO_{2.eq}$/MWh Report treeze (2014), **electricity mixes of certain countries**: More than 0.6 t $CO_{2.eq}$/MWh electricity (in subsection 3.2.2, examples are presented)
CED: 5.85 GJ_{prim}/MWh of electricity produced (not net)	Bacenetti et al. (2013), pig slurry vs. maize silage, **AD:** In certain cases and without taking into account the credits for the electricity from biogas, the energy consumption presented 2.29-4.01 GJ_{fossil}/MWh of produced electricity Report treeze (2014), **electricity mixes of certain countries**: More than 10 GJ-oil-eq/MWh electricity (in subsection 3.2.2, examples are presented)
ReCiPe midpoint with characterisation, Terrestrial acidification: 1.84 kg SO_2 eq/t of feedstock (taking into account both AD and transportation)	De Vries et al. (2012), pig manure, AD, Scenario «co-digestion of manure with wheat yeast concentrate», ReCiPe midpoint: 1.61 kg SO_2 eq per FU (FU: 1 t of substrate (fresh matter) added to the digester)
Annual production: 127 Nm^3 biogas/t of feedstock	Whiting and Azapagic (2014), feedstock (half: manure; the rest: cheese whey, waste maize silage and fodder beet), **AD**: 145 Nm^3 biogas/t of feedstock

3.2.3. Future prospects: Calculation of the avoided impact

As a future prospect, the boundaries of the present LCA could be extended in order to include additional components and stages of the proposed AD plant. For example, the impact related to the storage of the digestate as well as the environmental benefits associated with digestate composting and electricity production by using biogas could be taken into consideration.

It is known that maintaining soils that are healthy and productive is of great importance. AD digestate is a nutrient-rich slurry that can be used as fertiliser. Moreover, there are devices which separate the digestate into solid and liquid. For example, the solid part can be heat-dried in order to produce fertiliser pellets. The application of digestate to soils offers advantages such as increase in organic matter, reduction in the use of chemical fertilisers and pesticides, improvement of plant growth, reduction in soil erosion and increase in water-retention-ability of the soil (Source: EPA). The issues mentioned above are environmental advantages that, as a broader prospect, could be taken into account as avoided environmental impacts in the frame of an LCA study.

The environmental benefits from the use of AD digestate as fertiliser have been investigated, for instance by Ruiz et al. (2018). It was noted that there are avoided impacts due to the use of the digestate as fertiliser instead of using conventional fertilisers. Ruiz et al. (2018) found that the utilisation of the digestate from agri-food waste as a fertiliser improved the environmental profile of the AD system studied, especially in terms of human toxicity and freshwater ecotoxicity.

Finally, the avoided impact due to the production of electricity by means of an eco-friendly waste-management technology (AD/biogas) is an additional environmental benefit that could be taken into account. In subsection 3.2.2 a discussion about this issue, in relation to conventional electricity-production systems of several countries, has been presented.

4. CONCLUSIONS

The present article is an environmental LCA of a real-scale AD plant that has been developed in South France. The system uses 13652 t of feedstock (animal manure and other types of waste). The LCA has been conducted based on GWP, CED, ReCiPe midpoint/endpoint and USEtox. Different functional units have been adopted.

By taking into account the impact of both AD and transportation, the following findings have been found: 6430 t $CO_{2.eq}$ (based on GWP 100a); 67194 GJ_{prim} (according to CED); 231100 Pts (in terms of ReCiPe endpoint single-score: Human health), 146932 Pts (based on ReCiPe endpoint single-score: Ecosystems), 171568 Pts (according to ReCiPe endpoint single-score: Resources). With respect to USEtox method, the following results have been found: 1) Regarding Human toxicity/cancer, AD phase presents approximately 21 times higher impact in comparison to transportation, 2) In terms of Ecotoxicity, AD phase shows around 77 times higher score than transportation. By taking into account the impacts of both phases (AD; transportation), the results show the following values: 0.5-0.6 t $CO_{2.eq}$ per t of feedstock (or digestate) or per MWh of electricity produced (not net).

Regarding the participation of the animal manures to the total AD scores, percentages more than 31%, depending on the method/impact category, have been found. Concerning GWP and CED, a major part of the total GWP 100a (41%) and the total CED (50%) of AD is due to the animal manures. It has been found that poultry droppings present the highest scores (671 t $CO_{2.eq}$; 4662 GJ_{prim}). The animal waste with the second highest impact is sheep manure whereas cattle waste presents remarkably lower values in comparison to the other two types of animal waste (poultry droppings; sheep manure).

Finally, comparisons with literature are presented. In general, a good agreement has been observed. In addition, comparisons of the present findings (AD/biogas plant) with the impact of the electricity mixes of several countries have been included, proving the environmental advantages of the proposed AD system.

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